IAES International Journal of Artificial Intelligence (IJ-AI)
Vol. 14, No. 2, April 2025, pp. 1031~1048
ISSN: 2252-8938, DOI: 10.11591/ijai.v14.i2.pp1031-1048

Review of recent advances in non-invasive hemoglobin estimation

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Article Info

Article history:

Received Sep 24, 2024
Revised Nov 24, 2024
Accepted Jan 28, 2025

Keywords:

Artificial intelligence
Health monitoring
Hemoglobin
Machine learning
Non-invasive
Smartphone

ABSTRACT

Hemoglobin is essential for diagnosing conditions like anemia and respiratory issues. Traditionally, the assessment of hemoglobin necessitates invasive techniques that involve blood draws, which can induce discomfort and present possible complications for patients. Recent advancements in non-invasive technologies have light-emitting diode (LED) to the development of smartphone applications and machine learning algorithms that allow real-time hemoglobin level estimation, eliminating the need for blood sampling. This not only improves patient comfort but also enhances access to ongoing health monitoring. This review aims to delve into the newest developments in smartphone-oriented strategies for hemoglobin estimation, highlighting their importance within contemporary healthcare practices and the potential implications they might have for more expansive clinical applications. Technological advancements have combined smartphones and artificial intelligence (AI) for non-invasive hemoglobin estimation, offering a promising alternative to traditional methods. These solutions optimize data collection and analysis processes, enhance diagnoses' accuracy, and facilitate timely medical interventions. Advancements in technology have revolutionized medical diagnostics, particularly in estimating hemoglobin levels non-invasively. AI methodologies have demonstrated significant results in accurately forecasting hemoglobin concentrations through a variety of analytical strategies. Future research should focus on the best configurations for these networks and the physiological concepts underpinning spectral data interpretations.

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1. INTRODUCTION

The rising occurrence of anemia on a global scale underscores the pressing need for diagnostic tools that are both effective and easily accessible. Conventional methods of measuring hemoglobin typically require invasive procedures involving blood draws, which can cause discomfort and introduce risks for patients, especially in resource-limited settings. Recent advancements in technology have sought to confront these hurdles by utilizing the capabilities of smartphones and artificial intelligence (AI) for non-invasive estimations of hemoglobin levels. By integrating sophisticated algorithms alongside the internet of things (IoT), these new solutions present a promising alternative that could improve patient care while widening

access to crucial health evaluations. The combination of mobile technology and AI not only optimizes the processes of data collection and analysis but may also enhance the accuracy of diagnoses, thus facilitating timely medical interventions. This review aims to delve into the newest developments in smartphone-oriented strategies for hemoglobin estimation, highlighting their importance within contemporary healthcare practices and the potential implications they might have for more expansive clinical applications.

Hemoglobin, which is a significant biomarker within the human body, constitutes a protein located within red blood cells, and it plays an essential role in the processes of oxygen transport as well as the removal of carbon dioxide. Apart from its fundamental function in gas exchange, the quantification of hemoglobin levels serves as substantial indicators concerning overall health status and has implications for the diagnosis of conditions like anemia, various respiratory issues, and other he matological irregularities. Traditionally, the assessment of hemoglobin necessitates invasive techniques that involve blood draws, which can induce discomfort and present possible complications for patients. Nonetheless, recent innovations in the realm of non-invasive technologies have included the development of smartphone applications and machine learning algorithms that have significantly transformed this domain by permitting the estimation of hemoglobin levels in real-time, thus eliminating the requirement for conventional blood sampling [1]. These advancements not only improve the comfort experienced by patients but also enhance access to ongoing health monitoring, particularly in settings that are lacking resources, thereby underscoring the increasing significance of non-invasive hemoglobin evaluation within contemporary healthcare practices [2].

A variety of conventional methods for the assessment of hemoglobin levels have been utilized within the realm of clinical practice, each presenting particular methodologies alongside their respective limitations. The prevailing method, known as the complete blood count (CBC), engages venous blood samples which are subsequently analyzed within laboratory settings, thus yielding accurate hemoglobin measurements; nevertheless, this approach bears the characteristic of being invasive and requiring a significant duration, often demanding the involvement of trained personnel as well as specialized equipment. In another regard, pulse oximetry introduces a non-invasive methodology that estimates oxygen saturation and indirectly determines hemoglobin levels through the principle of light absorption. However, this technique is vulnerable to inaccuracies which may arise from diverse factors such as skin pigmentation and motion artifacts, ultimately compromising its dependability across varied populations. In addition, the visual inspection of blood samples utilizing colorimetric evaluations presents simplicity; nonetheless, it exhibits a deficiency in the accuracy requisite for sound medical decision-making [3]. Consequently, the ongoing demand for hemoglobin measurement techniques that are less invasive, expedited, and precise has fostered a conducive atmosphere for recent advancements that incorporate AI and smartphone technology.

The increasing dependence on invasive techniques for the estimation of hemoglobin, which includes venipuncture and capillary blood sampling, brings forth numerous significant challenges that detract from the wellbeing of patients as well as the efficiency of diagnostics. These approaches commonly result in discomfort and anxiety for patients, which may discourage them from pursuing necessary medical assessments, particularly within groups that are considered vulnerable. Additionally, these invasive methodologies come with intrinsic risks such as pain, bleeding, and the possibility of infection, thus raising questions regarding their comprehensive clinical utility [1]. Although they persist as the standard practice for many routine evaluations, the requirement for laboratory infrastructure alongside trained staff adds another layer of complexity to their accessibility, especially in settings that are constrained by resources [2]. In light of the ongoing transition in healthcare towards more patient-oriented strategies, the drawbacks of these invasive methods underline an urgent necessity for novel solutions that improve both the safety and the practicality of hemoglobin assessment, thereby facilitating the adoption of sophisticated non-invasive technologies, including smartphone applications integrated with AI and machine learning [4].

Innovative methods in the medical diagnostics sphere have been increasingly directed toward non-invasive techniques aimed at enhancing comfort for patients and improving accessibility. Among these developments, mobile health apps that implement AI alongside the IoT have surfaced as significant instruments for the estimation of hemoglobin levels. For example, recent research has indicated the effectiveness of using smartphone imaging combined with deep learning algorithms, which enables notably high accuracy in hemoglobin measurements, underscoring the utility of such systems in delivering real-time health evaluations without necessitating traditional blood analyses [1]. This transition not only aids in prompt clinical decision-making but also tackles the challenge of insufficient access to healthcare in low-resource regions. Additionally, the amalgamation of varied imaging methods, such as pulse oximetry and photoacoustic imaging (PAI), illustrates the potential to markedly enhance non-invasive practices, thus paving the way for a novel phase in diagnostics that is centered around the patient [2], [4].

Recent advancements in the realm of technologies for non-invasive estimation of hemoglobin levels are poised to potentially transform clinical practices and outcomes for patients. Innovations including smartphone applications that leverage deep learning techniques have exhibited notable accuracy in estimating

hemoglobin concentrations, surpassing both conventional methodologies and even the expertise of seasoned healthcare practitioners. The incorporation of AI alongside the IoT into these mechanisms not only amplifies capabilities for real-time monitoring but also enhances access in settings with limited resources [1]. Moreover, developments such as the amalgamation of principal component analysis (PCA) with back propagation artificial neural networks (BP-ANN) have yielded encouraging findings in the refinement of spectral data, leading to precise hemoglobin detection and providing measurements that are both robust and reliable [5]. As these technological innovations progress, they are anticipated to disrupt anemia screening protocols, promoting earlier detection and more customized treatment strategies, which could markedly influence global public health initiatives [4].

Recent progress in the non-invasive estimation of hemoglobin showcases an important convergence of technology within the realm of healthcare, addressing the necessity for diagnostic techniques that are both efficient and devoid of pain. At the core of this study is an examination of groundbreaking methodologies, for instance, smartphone applications that use deep learning algorithms aimed at enabling real-time predictions of hemoglobin levels, as indicated in [1]. These developments aim to mitigate the conventional hurdles linked with invasive blood sampling, thereby providing notable advantages concerning patient comfort and accessibility in diverse clinical environments. Additionally, the research underscores the use of artificial neural networks (ANN) and spectrophotometric systems, emphasizing the amalgamation of device-based approaches, which bolsters the capacity for non-invasive diagnostics to improve anemia screening, particularly within marginalized communities [5]. The study, through thorough scrutiny of these technologies, seeks to clarify their efficacy, possible drawbacks, and the greater ambition of revolutionizing hemoglobin estimation to bolster a decentralized model of healthcare while asserting the imperative for more research to substantiate these methodologies [6].

Recent advancements seen in non-invasive estimation of hemoglobin exemplify a notable merging of sophisticated technology with the field of healthcare, especially through the frameworks of AI and the IoT. This review takes a critical look at a variety of methodologies, placing significant emphasis on the incorporation of mobile applications that leverage deep learning algorithms to yield accurate hemoglobin readings via imaging techniques on smartphones [1]. The scope of this exploration encompasses an array of non-invasive techniques, which include spectrophotometric methods that exploit light-emitting diode (LED) light sources alongside intricate spectrographic systems, enhancing the feasibility for early diagnosis of anemia without the necessity of conventional blood draws [5]. Moreover, the evaluation of disparate biosensing modalities, encompassing pulse oximetry and PAI, further exposes the intricacies and inherent limitations regarding their application, thereby emphasizing the necessity for enhanced accuracy throughout various platforms [2]. Through the synthesis of current literature alongside ongoing technological progress, the review articulates a thorough framework for the prospective future of non-invasive hemoglobin monitoring, whilst underscoring potential pathways for subsequent research and developmental work.

In the last few years, notable advancements have been observed in the domain of non-invasive estimation of hemoglobin, capitalizing on AI as well as the IoT to bolster diagnostic efficacy. As previously outlined in the earlier sections, the amalgamation of sophisticated machine learning methodologies with smartphone technology enables immediate analytical capability, presenting a promising substitute to conventional blood analysis. The study discusses the methodological innovations, such as the utilization of deep learning frameworks and optical methods, which yield nuanced perspectives into hemoglobin concentrations with commendable precision [1], [2]. Additionally, the obstacles encountered by prevailing technologies, which encompass concerns regarding accessibility and dependability, are scrutinized critically, thereby paving the route for prospective advancements [7]. Such progressing technologies not only enhance patient outcomes but also underscore a transformative shift towards increasingly decentralized and user-centric healthcare solutions, accentuating the pressing necessity for ongoing inquiry in this critical field.

2. TECHNOLOGICAL INNOVATIONS IN NON-INVASIVE HEMOGLOBIN ESTIMATION

The advancements in AI and the IoTs have significantly changed the field of non-invasive hemoglobin estimation, leading to the development of more convenient and effective healthcare solutions, as illustrated in Figure 1. The use of AI in hemoglobin estimation involves various other technological aspects, such as sensors, digital signal processing in the form of photoplethysmography (PPG), databases, and AI computing itself. People commonly use the PPG signal noninvasively to measure hemoglobin concentration in blood. Using smartphone technology, researchers have developed applications that combine deep learning algorithms to analyze images of peripheral tissues, like eyelids, and predict hemoglobin levels with significant accuracy; a study shows a mean absolute error (MAE) of 1.34 g/dL for hemoglobin estimation. In addition, new developments like the combination of broadband light sources, grating spectrographs, and ANN show that portable devices can be used to get accurate measurements, which makes the case for decentralized healthcare even stronger [5]. These technological advances not only make measurements more

accurate, but they also make it easier to keep an eye on things in real time. This meets the clinical need for quickly diagnosing and treating anemia in a wide range of patient groups [1], [3].

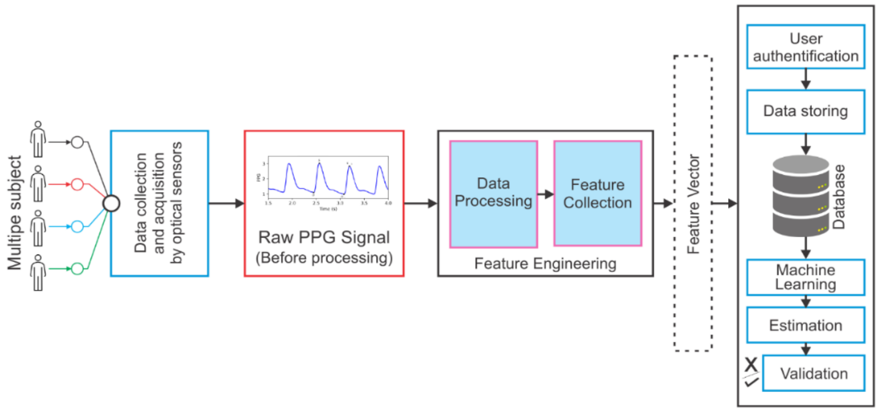


Figure 1. Diagram block of AI method for hemoglobin measurement based on PPG signal

2.1. Overview of non-invasive technologies

Emerging methodologies for the estimation of hemoglobin do utilize advancements in optical technology along with AI, which in turn redefines non-invasive diagnostics in healthcare. Recent developments incorporate the use of smartphone applications in conjunction with advanced imaging modalities, including deep learning models, for the precise assessment of hemoglobin levels merely through the capture of images of the eyelids, as presented by Chen *et al.* [1]. Additional significant techniques employ optical spectrophotometry alongside neural networks for the analysis of blood, where PCA is implemented to enhance the precision of hemoglobin predictions by effectively reducing data redundancy [5]. Moreover, novel strategies that tackle issues of racial bias within pulse oximetry underline an essential requirement for diverse testing technologies that can accommodate a broader patient demographic [2]. These non-invasive alternatives offer not only enhanced patient comfort and adherence but also improved accessibility in low-resource environments, thus accentuating the transformative potential linked to the integration of the IoT within the realm of healthcare [1], [4]. In recent years, the development of non-invasive hemoglobin estimation device technology has grown rapidly, where the use of optical-based sensors and image processing has become the most popular research topics. Table 1 shows a summary of hemoglobin estimation devices that have been developed by many researchers based on the sensors used, the signals processed and the body area that is the object of measurement.

Table 1. Summary of different non-invasive devices technologies for hemoglobin measurement

Reference	Device	Sensor	Signal	Body part
Kavsaoglu *et al.* [8]	Hemocue Hb-201	PPG	Light	Finger
Kim *et al.* [9]	Spectrometer, quartz-tungsten-halogen source	Optical	Spectra	Conjunctiva
Nirupa *et al.* [10]	Prototype	PPG	Light	Finger
Ding *et al.* [5]	LED and photodiode	Optical	Spectra	Finger
Timm *et al.* [11]	InGaAs photodiode	Optical	Spectra	Finger
Pothisarn *et al.* [12]	Analyzer oximetry	Optical	Light	Finger
Nguyen *et al.* [13]	XE-2100, Masimo Radical 7	Fluorescence and optical	Pulse	Finger
Jeon *et al.* [14]	Hardware prototype	Optical	Pulse	Finger
Jakovels *et al.* [15]	Nuance 2.4	Optical	Spectra	Skin
Timm *et al.* [16]	Hemocue	Optical	Spectra	Finger
Wang *et al.* [17]	Masimo Pronto 7, red, green, blue (RGB) complementary metal oxide semiconductor (CMOS) camera	Image	PPG	Fingertip
Kamr ul *et al.* [18]	Smartphone camera	Image	PPG	Finger
Wang *et al.* [19]	Smartphone camera	Image	PPG	Finger
Kuestner *et al.* [20]	Modified pulse oximeter, Coulter STKS Monitor	Optical	Spectra	Finger, ear, or toe
Lamhaut *et al.* [21]	Hemocue 201+, Radical-7	Optical	Spectra	Finger or ear
Jakovels *et al.* [22]	RGB CMOS	Optical	Spectra	Arm
Miyashita *et al.* [23]	R1-25 and R2-25a	Optical	Spectra	Finger
Li *et al.* [24]	AvaSpec HS1024x58TEC-USB2	Optical	Spectra	Finger
Frasca *et al.* [25]	Hemocue 301, Siemens RapidPoint 405 Sysmex XT 2000i	Optical	Spectra	Finger

2.2. Spectroscopy techniques

The progression of non-invasive techniques for hemoglobin estimation has experienced notable developments via innovative spectroscopy methods that emphasize precision and wider accessibility. Utilizing spectrophotometric approaches, recent investigations reveal encouraging substitutes for conventional blood testing. The incorporation of AI into spectroscopy, notably through BP-ANN in conjunction with PCA, has significantly enhanced the ability to predict hemoglobin levels from fingertip spectral information, reaching a correlation coefficient of 0.94, as referenced in [5]. Additionally, advancements in mobile imaging technologies and wearable instruments permit ongoing and immediate observation of blood metrics, which aids in prompt clinical evaluations devoid of the discomfort associated with venipuncture [1]. Furthermore, these methodologies tackle important issues that exist in traditional practices, such as their vulnerability to motion disturbances and the variability linked to patient characteristics, highlighting the necessity for standardized optical measurement techniques [2]. In conclusion, the melding of these approaches indicates a considerable advancement towards more effective and patient-oriented healthcare solutions. Summary of spectra-based techniques for non-invasive hemoglobin measurement is presented in Table 2.

Table 2. Summary of spectra-based techniques proposed for non-invasive hemoglobin measurement

Reference	Wavelength (nm)	Comparator	Signal	Participants (N)
Yi *et al*. [26]	600-1,100	Hematology analyzer (Pentra 60; ABX; France)	PPG	220
Rochmanto *et al.* [27]	670, 940	Sysmex-KN21	PPG	78
Desai *et al*. [28]	530	Pronto-7, Hemocue Hb analyzer	PPG	10
Kavsaoglu *et al*. [8]	660, 905	Hemocue Hb-201TM	PPG	33
Kim *et al*. [9]	400-700	Standard CBC test	Photon	32
Nirupa *et al*. [10]	624, 850	Prototype	PPG	69
Ding *et al*. [5]	600-1,050	LED and photodiode	Spectra	119
Bremmer *et al*. [29]	350-1,050	Ocean Optics DH-2000	Spectra	8
Timm *et al*. [11]	600-1,000	LED	PPG	48
Fuksis *et al*. [30]	760-940	infrared (IR) LED_s	Spectra	—
Pothisarn *et al*. [12]	660, 940	Analyzer oximetry	Light	—
Nguyen *et al*. [13]	940	Radical 7, XE-2100	Pulse	41
Jeon *et al*. [14]	569, 660, 805, 880, 940, 975	Hemoglobin cyanide method	Pulse	129
Jakovels [15]	500-700	White LED	Spectra	—
Timm *et al*. [16]	600-1,400	OxyTrue Hb	Spectra	1,008
Wang *et al*. [17]	500-700, 1,300	Masimo Pronto 7, RGB CMOS camera	PPG	32
Suzaki *et al*. [31]	600, 625, 660, 760, 800, 940, 1,300	K1713-09 Hamamatsu Photonics, co-oximeter	Light	—
Al-Baradie *et al*. [32]	670	Hemo Cue	PPG	10

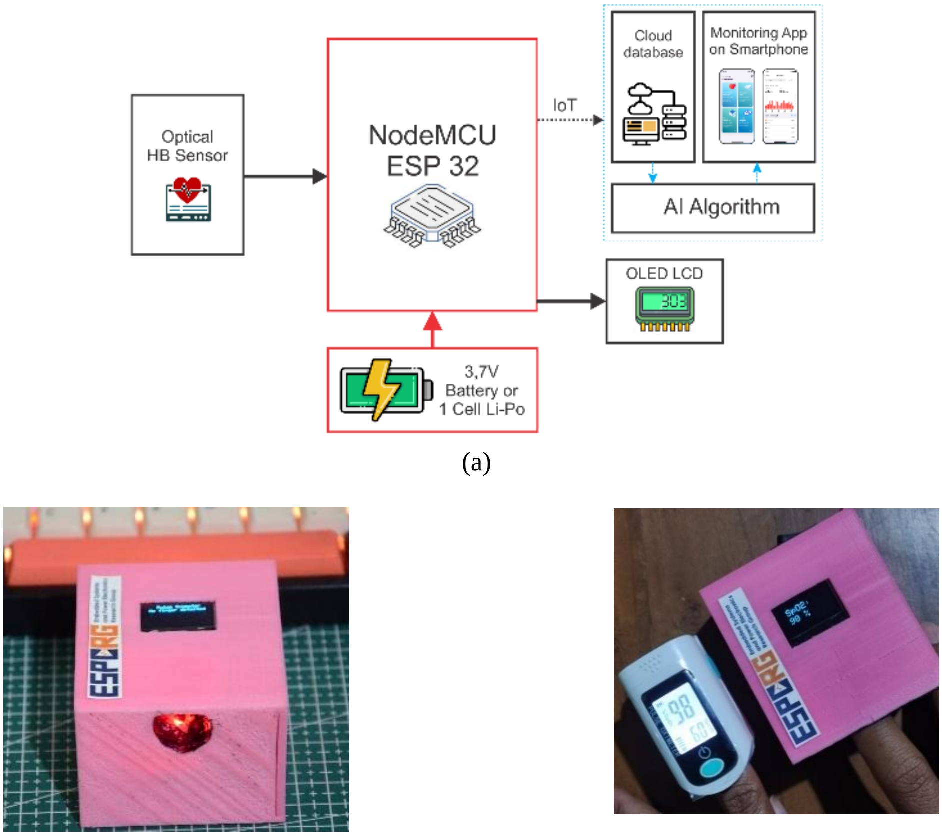
2.3. Pulse oximetry advances

Recent advancements in technology have notably enhanced the functionalities of pulse oximetry, specifically regarding its precision and applicability in various clinical contexts. Developments in sensing technologies, which includes the use of AI algorithms, have LED to improvements in real-time evaluations of blood oxygen saturation levels, as well as more dependable assessments of hemoglobin concentrations. Such advancements tackle the limitations that traditional pulse oximetry has always faced, including its sensitivity to motion artifacts and the racial biases that have historically LED to unsatisfactory readings in certain groups of individuals. Furthermore, machine learning methodologies, in conjunction with the adoption of IoT, serve to enhance the dependability of these systems by facilitating continuous monitoring and data evaluation, a crucial aspect for managing conditions like chronic obstructive pulmonary disease (COPD) and cardiovascular diseases [3]. In conclusion, these innovations establish pulse oximetry as an essential tool not merely for immediate patient evaluations, but also for the ongoing management of chronic health issues, thus paving the path for more tailored and accessible health care options.

Recent advancements have been noted in non-invasive diagnostic technologies which have greatly altered the medical imaging sphere, specifically concerning hemoglobin estimation. Utilizing methods such as optical coherence tomography (OCT), investigators are able to capture high-resolution, cross-sectional images of biological tissues. This capability enhances the visualization of crucial microvasculature needed for diagnosing conditions like anemia. The non-invasive characteristic of OCT is in alignment with the escalating need for patient-friendly diagnostic approaches, given that traditional blood sampling may present discomfort and introduce certain risks [33]. In addition, optical coherence tomography angiography (OCTA) has surfaced as a efficacious instrument for evaluating vascular structures, permitting detailed analysis without necessitating contrast agents, thus facilitating a more streamlined diagnostic pathway [34]. Moreover, the combination of these advanced optical methodologies with AI models appears promising, not

merely for bolstering accuracy but also for enabling real-time hemoglobin monitoring, which could advance more effective and accessible patient care across various clinical environments.

This study has developed pulse oximetry sensors for non-invasive hemoglobin measurement, as illustrated in Figure 2. We have combined optical sensors with the NodeMCU ESP32, which serves as a processor and IoT protocol, to transmit data from the device to the cloud database. Figure 2(a) depicts a block diagram of the developed systems, while Figures 2(b) and 2(c) feature photographs of the developed device. Table 3 presents the results of SpO2 measurements using the developed device, and compares the data with existing devices on the market. The results indicate that the average error for all patients tested in this research is less than 1%, demonstrating the effectiveness of the developed pulse oximetry device.



(a)

(b) (c)

Figure 2. Experimental device depeloped by author: (a) diagram block of the system, (b) device front view, and (c) developed device calibration process.

Table 3. The result of SpO2 measurements using non-invasive device

Patients	Pulse oxymeter value (%)	Value of the developed device (%)	Average error (%)
Patient 1	97.6	97.4	0.204081633
Patient 2	97.4	98.2	0.829037801
Patient 3	97	96.6	0.4102672
Patient 4	96.8	97	0.620704467
Patient 5	98.2	98.2	0.408163265
Patient 6	98	97.4	0.610183467
Patient 7	97.6	97	0.61662815
Patient 8	97.8	96.8	1.022512098

2.4. Photoacoustic imaging

Recent advancements in technology have notably augmented the feasibility of estimating hemoglobin levels non-invasively through the utilization of PAI. This novel methodology leverages the interactions occurring between pulsed laser light and biological tissues, thus enabling the gathering of

real-time spatial data related to blood oxygenation without the need for invasive methodologies. Research has indicated that PAI can yield precise evaluations of internal jugular venous oxygen saturation (sijvO2), which is crucial for the assessment of cerebral oxygenation in instances such as stroke and head trauma [35]. Furthermore, sophisticated machine learning algorithms, akin to those that are incorporated into smartphone technologies, have the potential to augment the efficacy of PAI by refining data processing and interpretation [1]. This amalgamation of PAI with AI represents a significant transformation in the realm of healthcare, as it not only accelerates diagnostic procedures but also reduces the hazards tied to conventional blood sampling techniques. Overcoming the limitations inherent in traditional methodologies facilitates broader implementation in clinical settings [2].

2.5. Wearable technology developments

Recent advancements regarding portable health monitoring apparatus are disrupting patient care paradigms through improved accessibility and convenience, notably within the arena of non-invasive hemoglobin measurement. Utilizing sophisticated spectrophotometric methodologies, particularly those that incorporate BP-ANN alongside PCA, investigative efforts have noted progress in the precise estimation of hemoglobin quantities from fingertip spectral data. Such outcomes bolster the viability of devices that amalgamate machine learning techniques for efficacious health diagnostics, reflecting observable trends in wearable technology tailored for chronic ailment management. For example, research underscores how intelligent devices for managing incontinence enhance the quality of life for those suffering from urological ailments, thus signifying a pressing necessity for innovation within the realm of wearable health technology [36]. Moreover, through the application of smartphone applications paired with optical sensors, non-invasive methodologies can yield real-time analytics while fostering decentralized healthcare frameworks, thereby tackling challenges endemic to conventional clinical environments [1], [2].

2.6. Integration of artificial intelligence

Recent advancements pertaining to smartphone technologies and AI have notably altered the context regarding non-invasive hemoglobin estimation. By incorporating AI algorithms, researchers have heightened the precision of hemoglobin level predictions based on optical imaging methodologies, like those that utilize smartphone cameras alongside spectrophotometric systems. For example, investigations employing convolutional neural networks (CNN) have attained significant performance gains in analyzing eyelid imagery for the non-invasive assessment of hemoglobin concentrations, as evidenced by an indicated mean L1 error of 0.72 g/dL [1]. This progress signifies a wider movement within the discipline, coinciding with existing efforts to integrate AI into medical imaging for the enhancement of diagnostic procedures. Moreover, as evaluated in Moreno *et al.* [37], the amalgamation of conventional imaging techniques with AI-enhanced approaches has broadened the effectiveness of multiparametric magnetic resonance imaging (MRI) in the realm of prostate cancer, illustrating AI's capacity to transform multiple diagnostic domains. The capability to leverage extensive datasets and execute machine learning models, as demonstrated in [38], is imperative to surmount existing challenges in clinical practice, thereby facilitating enhanced patient outcomes regarding conditions like anemia.

2.7. Role of the internet of things

Innovations what pertain to mobile technology, especially through the IoT, undertaking a quite substantial role in healthcare diagnostics by enabling monitoring of vital health metrics in real-time and in a non-invasive manner, hemoglobin levels included. Utilizing IoT facilitates the integration of various sensors and numerous devices that communicate and exchange data without issues, thus improving the accuracy and efficiency of health assessments. For instance, the usage of smartphone applications, when paired with algorithms of AI, demonstrates capacity to intelligibly process and analyze data from non-invasive measurements regarding hemoglobin concentrations, thereby making advanced diagnostics achievable even in settings with limited resources [7]. These advancements not only render health monitoring more accessible but also give power to individuals through real-time insights about their health, which greatly aids in timely interventions concerning conditions like anemia, affecting nearly 25% of the global population [2]. The future of IoT within healthcare is predicated on its capability to perpetually improve data security and the interoperability among devices, which ultimately intends to advance patient care through the concept of personalized medicine [39].

3. SMARTPHONE-BASED NON-INVASIVE HEMOGLOBIN ESTIMATION

The amalgamation of progressive technologies within the healthcare sector is engendering novel methodologies for conventional medical diagnostics. Notably, the smartphone-driven non-invasive hemoglobin evaluation has risen as a notable improvement, merging ease of use with precision. This

approach exploits the all-pervasive nature of smartphones in conjunction with intricate algorithms to yield instantaneous hemoglobin assessments sans the necessity for blood samples. For example, the implementation of PPG to scrutinize alterations in blood volume within capillaries has been demonstrated to be beneficial for approximating hemoglobin concentrations, as highlighted in contemporary investigations which show a favorable correlation with traditional laboratory techniques [40]. Such methodologies, especially in areas with high accessibility, can enable prompt intervention for ailments such as anemia, thus permitting swift screening in jurisdictions with limited resources [2]. By utilizing machine learning frameworks, the predictive efficiency regarding hemoglobin concentrations is notably augmented, thereby proffering a hopeful substitute to traditional diagnostic methods and tackling inequities in healthcare availability [1].

3.1. Rise of smartphone applications

Recent tech advancements have notably changed the health monitoring field, leveraging the widespread nature of smartphones and their considerable computing power. The merging of AI with mobile applications has resulted in new non-invasive techniques for hemoglobin measurement, allowing users to conveniently obtain important health information. For example, research has shown the effectiveness of deep learning models used via mobile applications to interpret facial videos for extracting key data such as heart rate and blood pressure, mirroring a larger movement towards immediate health evaluations [41]. Furthermore, studies indicate that devices compatible with smartphones, which employ methods like PCA and BP-ANN, can reliably estimate hemoglobin concentrations based on spectral data from fingertips [5]. These innovations represent a significant change in personal healthcare, rendering it more attainable for individuals, particularly in areas with limited resources, to take part in proactive management of their health through mobile technology and AI advancements.

3.2. Mobile health innovations

The incorporation of advanced technologies into the healthcare domain has undergone considerable change, particularly with the rise of smartphone applications that harness AI and the IoT. These innovations have remarkably improved the access and effectiveness of non-invasive diagnostic techniques, such as the estimation of hemoglobin levels. By employing deep learning algorithms, devices are now capable of evaluating visual information captured via smartphones to accurately forecast hemoglobin concentrations, as indicated by studies that report strong performance results with limited computational needs [1]. This movement towards mobile health innovations not only allows for prompt health evaluations but also empowers individuals to take charge of their health proactively, which is vital for tackling global health issues, anemia included. Such advancements are consistent with the sustainable development goals (SDGs), particularly in improving the quality and equity of healthcare [42]. With ongoing technological progress, further developments are expected, potentially incorporating biosensors that track an array of physiological indicators, thereby ultimately enhancing patient care and clinical decision-making [43].

3.3. Algorithms for hemoglobin estimation

Technological advancements in recent times have noticeably altered the arena of non-invasive hemoglobin estimation, especially through the creation of complex algorithms. Utilizing the capabilities of AI, with an emphasis on deep learning methods, researchers have shown significant enhancements in the accuracy of measurements. As an example, a smartphone app that makes use of an efficient group enhanced (EGE)-UNet deep learning model has attained noteworthy performance metrics for hemoglobin prediction, recording a MAE of merely 1.34 g/dL, which is superior to conventional techniques like pulse oximetry that frequently encounter problems related to bias and precision shortcomings [1]. On a similar note, the amalgamation of PCA and BP-ANN has facilitated the creation of spectrophotometric systems that exhibit correlation coefficients as high as 0.94, underscoring the strength of these algorithms across diverse conditions [5]. These developments are crucial not just for improving diagnostic accuracy but also for broadening access, which ultimately reshapes patient care in both clinical and remote environments.

3.4. User interface and experience design

The emergence of non-invasive hemoglobin measurement technologies necessitates an emphasis on user interface and experience design (UI/UX), which is crucial for fostering efficient interaction between users and the increasingly intricate systems involved. User interfaces that are engaging are capable of significantly improving both accessibility and usability, especially for applications that cater to diverse populations, including those situated in low-resource environments. Adopting a user-centric design methodology guarantees that the interfaces utilized in devices, such as smartphone applications aimed at assessing hemoglobin levels, are intuitive and responsive to the requirements of users, as demonstrated in [1].

Furthermore, the incorporation of advanced technologies, like AI and IoT, must prioritize smooth interaction; failing to do so risks creating a disconnect with users who may not be familiar with these technologies. These concepts are supported by findings in [44], where functional near-infrared spectroscopy (fNIRS) was effectively utilized via a user-friendly interface, thereby improving data collection. Well-designed user interfaces extend beyond mere aesthetics; they are essential for ensuring that innovations remain both practical and advantageous for end-users, thereby highlighting the importance of design in the effective use of technology within medical diagnostics.

3.5. Data collection and analysis

The amalgamation of sophisticated techniques for data collection aptly improves the accuracy alongside the dependability of non-invasive estimations of hemoglobin levels. Contemporary investigations utilizing AI, especially deep learning frameworks, are transformative in the realm of data examination by adeptly handling extensive collections of spectral data sourced from groundbreaking smartphone-based imaging technologies. For example, the usage of EGE-UNet for the segmentation of eyelids within smartphone-acquired images has produced noteworthy performance indicators, illustrating the capacity of such systems to address the deficiencies found in traditional methodologies [1]. Concurrently, the application of machine learning paradigms, such as BP-ANN paired with PCA, reveals optimistic outcomes in the extraction of pivotal characteristics from intricate datasets, as demonstrated by a notable correlation coefficient of 0.94 in testing scenarios [5]. These methodologies accentuate how contemporary analytical techniques, integrated with advanced signal processing methods, enable precise and immediate evaluations of hemoglobin, thereby emphasizing their significance in the domains of clinical diagnostics and patient management [45].

3.6. Case studies of successful applications

The contemporary progressions in technological realms have culminated in numerous efficacious applications concerning non-invasive hemoglobin estimation, thereby evincing the prospective utility of these methodologies within clinical contexts. As an illustration, a particular inquiry employed deep learning methodologies that culminated in commendable precision concerning hemoglobin level prognostication via smartphone imaging. This exemplifies the ability of mobile technology to enable instantaneous health evaluations, especially pertinent to anemia screening [1]. Such a pioneering tactic diverges markedly from conventional approaches, which frequently necessitate distressing blood withdrawals and may be influenced by racial prejudices that could compromise treatment outcomes [2]. Furthermore, a spectrophotometric system that has been conceived employing PCA alongside BP-ANN proficiently ascertained hemoglobin levels from fingertip spectral data, showcasing a significant correlation coefficient. This underlines a noteworthy reliability in the identification of anemia absent any invasive techniques [5]. These exemplifications accentuate the disruptive potential inherent in the amalgamation of AI with avant-garde optical technologies pertaining to non-invasive diagnostics and advocate for a more extensive adoption within the healthcare sector.

3.7. Challenges in smartphone-based estimation

The incorporation of smartphone technology into the estimation of hemoglobin concentration that is non-invasive does encounter several significant obstacles that require attention to facilitate broader use and precision. A major issue is the inconsistency of ambient light conditions at the time of image acquisition, which can considerably impact how well the algorithms perform. Furthermore, the physiological variations among individuals, such as differing skin tones and types, may result in biases influencing the predictive accuracy of these algorithms, mirroring problems faced in existing techniques like pulse oximetry, where discrepancies related to race have been noted [2]. Additionally, the intricacies involved in accurately gauging hemoglobin levels via smartphone cameras demand the development of sophisticated algorithms that can effectively filter out noise and artifacts that are apparent in image data. Present methodologies, including those employing deep learning frameworks, do exhibit potential but frequently depend on considerable data augmentation to achieve elevated performance metrics [1]. In summation, thorough validation and standardization procedures are vital for addressing these challenges and guaranteeing dependable estimates of hemoglobin through smartphone technology [4].

3.8. Future directions for smartphone technology

With the convergence of advancements in AI alongside the IoT and smartphone technology, the prospect for non-invasive medical diagnostics appears to be considerably more hopeful. Future endeavors ought to concentrate on augmenting the integration of deep learning algorithms, such as EGE-Unet, utilized in groundbreaking methods of hemoglobin estimation, which would permit real-time data analysis to occur directly within mobile applications. Moreover, capitalizing on the distinctive capabilities inherent to smartphones, encompassing high-resolution cameras and an array of sensors, may enable more precise

measurements spanning diverse demographic groups, which is crucial for addressing the shortcomings noted in conventional pulse oximetry that frequently reveals racial bias [2]. Furthermore, it will be imperative to establish standardized protocols regarding image capture as well as algorithm enhancement to ensure the dependability and precision associated with smartphone-based diagnostic methods, thus constructing a resilient framework for widespread clinical adoption [1], [4]. Ultimately, the evolution of this technology signals a significant transformation in patient care, rendering health assessments increasingly accessible and tailored to individual needs.

4. ARTIFICIAL INTELLIGENCE IN HEMOGLOBIN ESTIMATION

Recent advancements in technology have enabled novel methodologies in the realm of medical diagnostics, especially regarding the estimation of hemoglobin levels in a non-invasive manner. By employing AI methodologies, scholars have indicated notable outcomes in the precise forecasting of hemoglobin concentrations through diverse analytical strategies. For example, one study that utilized a deep learning framework combined with smartphone imaging succeeded in attaining elevated accuracy metrics, thereby considerably improving patient access to haemoglobin evaluations without the necessity of invasive techniques [1]. Moreover, the employment of machine learning algorithms within spectral analysis has enhanced the effectiveness of hemoglobin detection apparatuses, exhibiting reliability levels akin to those of conventional methods. As noted in the analysis concerning AI's role in radiomics pertinent to prostate cancer, analogous structures may be translated to augment predictive modeling within the context of hematological diagnostics [38]. Such developments signify not merely a transition toward decentralized healthcare systems but also accentuate the transformative capabilities of AI in refining patient care via instantaneous monitoring and diagnostic practices, as shown in Figure 3.

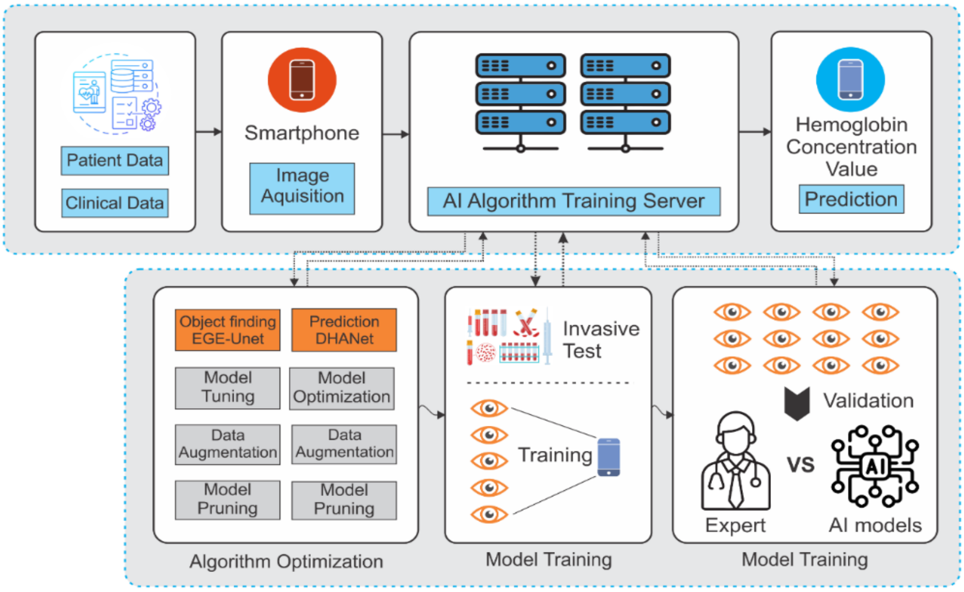


Figure 3. Diagram of AI method for hemoglobin measurement based on image acquisition

4.1. Machine learning techniques

Recent advancements within the realm of non-invasive hemoglobin estimation have received considerable advantages through the integration of machine learning methodologies, which enable the dissection of intricate biomedical datasets. The use of techniques such as deep learning and ANN has played a crucial role in augmenting both the precision and efficiency of hemoglobin level forecasts derived from PPG as well as smartphone imaging. Findings as articulated by Nair *et al.* [40] elucidate how refined machine learning models that have undergone training on substantial datasets are capable of establishing connections between PPG data and the conventional CBC assessments, thus exhibiting strong predictive functions. In a similar vein, the methodology discussed in [46] employs smartphone cameras to obtain fingertip PPG, with subsequent evaluations utilizing advanced machine learning algorithms aimed at

amplifying the accuracy of hemoglobin estimations. The adoption of strategies like PCA contributes additional refinement to these predictive frameworks, as demonstrated in research where the relationships between spectral data and true hemoglobin levels attained notable accuracy, thus highlighting the revolutionary potential that machine learning holds in progressing non-invasive diagnostic techniques, such as hemoglobin estimation [5].

4.2. Deep learning applications

Recent advancements in the realms of AI and smartphone technology have acted as a facilitative force leading to notable enhancements in non-invasive hemoglobin estimation methodologies. The integration of deep learning approaches has significantly altered the landscape of data analysis, allowing for improved predictions concerning hemoglobin concentrations drawn from intricate biological signal patterns. For example, strategies employing deep learning frameworks, including CNN, have showcased considerable effectiveness in the analysis of images aimed at hemoglobin quantification, which is substantiated by the successful non-invasive methodologies that exploit smartphone imaging capabilities [1]. In addition, the amalgamation of deep learning with other sophisticated technologies, like microfluidics and optical sensing mechanisms, has paved the way for rapid and real-time measurement processes, thereby addressing the restrictions associated with conventional techniques [2]. The capacity to formulate predictive models from large-scale datasets not only bolsters diagnostic precision but also facilitates wider access to healthcare solutions, especially in contexts characterized by limited resources. In summary, these developments highlight the transformative capacity inherent in the deployment of deep learning applications within the healthcare sector, especially concerning non-invasive diagnostic practices.

4.3. Data training and validation

The effectiveness of estimating hemoglobin levels non-invasively is quite contingent upon comprehensive data training and validation methods. Recent research, including that conducted by Chen *et al.* [1], has notably utilized extensive data augmentation strategies intended to boost the training dataset, thereby achieving enhanced performance metrics evidenced by a mean intersection over union (MIOU) value of 0.78 alongside an accuracy rate of 0.97 in hemoglobin predictions. Furthermore, developments within the realm of ANN, especially the incorporation of PCA in conjunction with BP-ANN, have yielded favorable results with correlation coefficients reaching as elevated as 0.94 [5]. Such methodologies effectively curtail noise and redundancy present within the training datasets, thereby fortifying the robustness of the models during subsequent validation phases [1]. Hence, an organized approach pertaining to data training not only seeks to refine the performance of algorithms but also lays down a substantive groundwork for clinical utility, ensuring dependable results across a variety of demographic and situational contexts [47].

4.4. Predictive analytics in hemoglobin levels

The amalgamation of sophisticated machine learning methodologies into non-intrusive hemoglobin assessment is fundamentally altering clinical methodologies and bolstering predictive analytics concerning patient health oversight. Utilizing deep learning frameworks, notably the BP-ANN, investigators have succeeded in formulating exceedingly precise models for predicting hemoglobin concentrations from fingertip spectral data, attaining correlation coefficients reaching 0.94. This novel strategy facilitates instantaneous monitoring devoid of the inconvenience linked to conventional blood assays, which is especially advantageous in settings with limited resources [5]. Additionally, the engagement of PCA in these forecasting frameworks effectively diminishes data dimensionality while alleviating the impact of irrelevant variables, thereby enhancing accuracy in predictions [1]. As the field of predictive analytics progresses, the conjecture of intertwining these systems with IoT technologies is poised to engender unparalleled progressions in personalized healthcare and medical access [4].

4.5. Artificial intelligence-driven diagnostic tools

The incorporation of AI within diagnostic instruments signifies a considerable alteration in the realm of healthcare, markedly improving the precision and availability of non-invasive techniques for estimating hemoglobin levels. Recent developments in applications based on smartphones utilize deep learning algorithms for the analysis of imaging information, proficiently forecasting hemoglobin concentrations without necessitating traditional blood assays. For instance, Chen *et al*. [1] implemented a smartphone application that harnesses EGE-Unet and deep hierarchical attention-contextual convolutional capsule attention encoder (DHA-C3AE) deep learning frameworks, achieving noteworthy performance metrics (e.g., MAE of 1.34) that exceed those of conventional methodologies. Additionally, the application of ANN techniques alongside PCA has demonstrated considerable potential in preserving robustness in the face of data fluctuations, effectively diminishing dimensionality while boosting prediction accuracy [5]. These

AI-enabled diagnostic tools hold promise for democratizing hemoglobin screening, rendering it feasible for various populations, particularly those in low-resource contexts, to obtain timely health evaluations [1], [48].

4.6. Ethical considerations in artificial intelligence use

With the expanding incorporation of AI within the realm of healthcare, especially in methods for estimating hemoglobin levels non-invasively, it becomes ever more imperative to tackle the ethical ramifications associated with such technological implementations. It is essential to prioritize the protection of patient privacy and the safeguarding of sensitive health information, given that any breaches could result in considerable repercussions for both individuals and institutions alike. Additionally, the existence of potential biases in AI algorithms prompts significant apprehensions pertaining to equity in access to healthcare services. For instance, should the training datasets fail to adequately represent a variety of populations, it is plausible that discrepancies in the accuracy of hemoglobin measurements may manifest, thereby potentially worsening existing health inequities [2]. It is critical to uphold principles of equity, transparency, and responsibility within AI applications to cultivate trust among users and alleviate the risks associated with such technologies [49]. Ultimately, it is necessary to construct a comprehensive ethical framework that will steer the advancement and implementation of AI in non-invasive health diagnostics, aiming to secure positive outcomes while also safeguarding populations that are especially vulnerable.

4.7. Comparison of artificial intelligence models

Contemporary advancements pertaining to the estimation of hemoglobin through non-invasive methods have increasingly incorporated AI frameworks, which exhibit diverse levels of efficacy regarding their accuracy in prediction and practicality in application. Specifically, BP-ANN that are integrated with PCA have surfaced as a substantial approach for the detection of non-invasive hemoglobin, attaining a correlation coefficient of 0.94 amidst a variety of sample collections, as evidenced in investigations into novel spectrophotometric systems [5]. Conversely, CNNs that have been employed within smartphone imaging platforms have also evidenced optimistic results in relation to hemoglobin level estimation, with performance metrics that exceed those of conventional expert methodologies by a notable degree [1]. Nonetheless, these models are confronted with certain challenges; both grapple with concerns related to data noise and variability that are intrinsic to biological datasets, thus accentuating the importance of continuous efforts for optimization and validation in order to bolster their dependability in clinical applications [50], [51]. Consequently, whilst both BP-ANN and CNN frameworks provide pertinent insights, an analytical comparison delineating their individual strengths, limitations, and potential applications is crucial for the progressive enhancement of the domain of non-invasive hemoglobin estimation.

4.8. Future trends in artificial intelligence integration

Technological advancements are on the verge of reshaping the domain of non-invasive hemoglobin estimation, especially with the growing incorporation of AI in diagnostic operations. The utilization of deep learning models, exemplified by novel approaches like EGE-Unet and DHA(C3AE), indicates a notable enhancement in both the precision and accessibility of hemoglobin evaluations, implying that forthcoming trends will significantly depend on AI for the augmentation of imaging methodologies. Furthermore, the integration of AI with IoT technologies unlocks new pathways for instantaneous monitoring and data interpretation, as provided by studies showing mobile applications surpassing conventional techniques in terms of diagnostic accuracy [52]. As machine learning algorithms advance, it is highly probable that they will present customized diagnostic instruments, modifying analyses according to specific patient features and contextual environments, ultimately contributing to improved healthcare results across various settings [52].

5. CLINICAL APPLICATIONS AND IMPLICATIONS

The incorporation of technologies for estimating hemoglobin levels non-invasively into clinical environments holds considerable implications for the management of patients and their health results. New methods that employ sophisticated optical techniques along with algorithms including deep learning exhibit considerable potential for delivering prompt and precise hemoglobin measurements, all while eliminating the discomfort associated with traditional blood draws. For example, devices that have been created using PCA and BP-ANN show strong correlations with real hemoglobin levels, suggesting a likelihood for broad application in diagnosing anemia [2]. Additionally, the capability to continuously monitor hemoglobin concentrations could enhance the management of disorders such as COPD and diabetes, thereby making a notable difference in patient care through the facilitation of preemptive interventions [5]. As advancements in these technologies progress, they may also help to mitigate healthcare inequalities, especially in

resource-limited settings where the availability of traditional testing methods might be constrained, thereby ultimately contributing to a more balanced delivery of healthcare services [53].

5.1. Use in emergency medicine

Within the realm of emergency medicine, the technologies for estimation of hemoglobin that are non-invasive hold notable benefits that could essentially improve management of patients. The swift evaluation of hemoglobin levels holds substantial importance in emergency circumstances, like trauma or instances of acute hemorrhage, wherein timely action could be crucial for survival. Conventional methods of blood sampling, albeit precise, are invasive and protracted, thereby possibly hindering essential treatment. Modern developments, particularly those marrying smartphone technology with AI, facilitate more rapid, immediate evaluations devoid of the distress linked to typical venipuncture practices. For example, research that employs smartphone applications along with deep learning frameworks has reached commendable accuracy in hemoglobin estimation, with performance metrics like an F1 score recorded at 0.87 and a MAE measured at merely 1.34. Additionally, these advancements can be utilized in environments where resources are scarce, thereby narrowing the disparity between sophisticated medical care and real-world emergency response, emphasizing the groundbreaking potential that non-invasive methodologies possess in urgent clinical contexts [1], [54].

5.2. Monitoring chronic conditions

The amalgamation of cutting-edge non-invasive technologies presents noteworthy potential for the ongoing observation of chronic health issues, specifically within the sphere of hemoglobin assessment. Novel methodologies, inclusive of smartphone imaging in conjunction with deep learning algorithms, show commendable precision in evaluating hemoglobin levels without the unease linked to traditional practices. To illustrate, deep learning frameworks like EGE-Unet and DHA(C3AE) have recorded exceptional performance indices, directly estimating hemoglobin concentrations from images of the eyelid, thereby advancing clinical judgment in contexts such as preoperative reviews and the oversight of ailments, for instance, anemia. Furthermore, the use of portable, non-invasive instruments that employ techniques such as spectrophotometry alongside ANN further substantiates the capability to transform the availability and accuracy of hemoglobin assessment [1], [5]. This progression in technology is vital for the enactment of decentralized healthcare methodologies, ultimately enabling individuals with chronic ailments to secure improved health results while reducing the impediments conventionally encountered with standard diagnostic approaches [55].

5.3. Applications in maternal and child health

The integration of non-invasive hemoglobin estimation technologies presents notable promise within the domain of maternal and child health, especially in tackling the widespread problem of anemia in the contexts of both pregnancy and early childhood. Given the fact that anemia may result in dire health complications for both mothers and their infants, the significance of early detection becomes quite evident. Recent developments, such as smartphone-based applications that employ deep learning algorithms for hemoglobin forecasting, illustrate this promise effectively. These systems facilitate real-time evaluations, which become particularly essential in low-resource environments where traditional diagnostic approaches frequently prove to be impractical. The precision of these applications, evidenced by indicators like MAE, suggests a capacity to surpass standard techniques utilized by healthcare professionals, potentially enhancing clinical decision-making in maternal care [2]. Moreover, the introduction of portable and economical devices facilitates routine monitoring, thereby encouraging proactive interventions that could substantially improve health outcomes for at-risk populations [1], [56].

5.4. Role in blood donation and transfusion

The assurance of sufficient hemoglobin concentrations plays an essential role in both practices of blood donation and transfusion, having a direct correlation with the safety of patients as well as the effectiveness of treatments administered. Non-invasive technologies for estimating hemoglobin levels, particularly those that employ smartphone applications coupled with deep learning algorithms, have surfaced as noteworthy advancements in the realm of preclinical evaluations. Such innovations not only enable the conducting of assessments in real-time but also broaden accessibility, particularly in environments characterized by limited resources. Furthermore, the capacity to accurately determine hemoglobin levels through non-invasive means meets the pressing demand for secure screening methods regarding potential donors, thereby fostering an increase in participation rates [2]. Research findings suggest that non-invasive approaches may exhibit superior performance relative to traditional methodologies, thus reducing risks linked to blood donation and enhancing the safety profile associated with transfusions [1]. Through the integration

of these emerging technologies, healthcare practitioners are equipped to make well-informed decisions, improving transfusion outcomes and, in the long run, contributing positively to patient care [57].

5.5. Impact on global health initiatives

The progress associated with non-invasive methods for hemoglobin estimation presents noteworthy potential benefits for global health efforts, particularly in the fight against anemia, which reportedly impacts around 24.8% of individuals worldwide. As pointed out in [1], the amalgamation of smartphone technology and deep learning serves as an immediate, easily accessible option for measuring hemoglobin concentrations, consequently minimizing dependency on invasive techniques that might incur health hazards. Such a groundbreaking tactic can be especially advantageous in resource-limited areas where conventional diagnostic instruments are potentially sparse or unavailable. In addition, Taylor-Williams *et al.* [2] underscores the importance of dependable measurement methodologies, especially for underprivileged groups that often face biases within healthcare, an issue similarly prevalent in pulse oximetry. The capacity of these non-invasive strategies to produce precise results could significantly improve disease monitoring and preventative healthcare, thereby enhancing public health goals and supporting broader access to healthcare on a global scale. In conclusion, the convergence of technological innovations with health services may rejuvenate anemia detection and treatment strategies, ultimately serving the needs of marginalized populations.

5.6. Cost-effectiveness of non-invasive methods

Recent occurrences in the realm of non-invasive hemoglobin assessment underscore the possible monetary benefits contrasted with established methodologies, especially when considering the elevated expenses and logistical hurdles related to invasive techniques. Particularly, mobile software applications that employ deep learning technologies, as evidenced by the studies conducted by Chen *et al.* [1], have shown not only an enhancement in precision-attaining a MAE of 1.34 g/dL-but also furnish instantaneous diagnostic capabilities that can be smoothly integrated into the current healthcare systems. In addition, the incorporation of IoT functionalities enables broader availability, especially in settings with limited resources, thereby leading to a reduction in total healthcare expenditures connected to anemia evaluations [1]. The progress of portable spectrophotometric instruments, as discussed in previous scholarly work, illustrates a growing movement towards the democratization of health diagnostics, ultimately fostering cost efficiency by decreasing the necessity for specialized medical infrastructure and lessening the travel time for patients, alongside associated healthcare costs [58].

5.7. Patient acceptance and compliance

The efficacy of methods for estimating hemoglobin levels without invasive techniques greatly depends on how well patients accept and comply with these procedures. As such innovations pursue the goal of providing unobtrusive healthcare experiences, it becomes essential to comprehend the perspectives of patients regarding these newly introduced technologies. Non-invasive approaches, including those that employ smartphone applications and deep learning algorithms for the evaluation of hemoglobin, are conspicuously less invasive than conventional blood sampling methods, which in turn augments patient comfort and overall satisfaction. Moreover, developments within the realm of mobile health technology, which offer real-time feedback along with the ease of conducting tests at home, could favorably impact adherence to recommended screening practices, particularly among varied demographic groups experiencing anemia [2]. Nevertheless, obstacles continue to exist, such as the need to assure that patients possess confidence in the precision of these non-invasive alternatives. It is crucial to cultivate trust through effective educational initiatives and transparent communication concerning the advantages and limitations inherent to these technologies; this will be vital for their broad acceptance and improved patient compliance regarding protocols for hemoglobin monitoring [1], [49].

5.8. Regulatory and standardization issues

The incorporation of non-invasive technologies for estimating hemoglobin levels into the realm of clinical practice encounters a variety of regulatory and standardization obstacles. The swift evolution of these technologies, notably with enhancements in AI and smartphone capabilities, is often obstructed by the absence of definitive regulatory structures, which can impede their widespread utilization. Existing approaches, exemplified by the application of deep learning algorithms aimed at hemoglobin measurement through smartphone imaging, exhibit notable precision; however, they are frequently deficient in standardized validation protocols, which are vital for gaining regulatory acceptance002E In addition, non-invasive devices, which often leverage optical techniques, must tackle inconsistencies arising from user equipment and varying measurement environments, as these factors are crucial for ensuring dependability and consistency across heterogeneous populations [2]. A collaborative strategy that brings together

regulatory agencies, manufacturers, and researchers is imperative to formulate thorough guidelines that guarantee the safety, effectiveness, and standardization of these diagnostic tools. Such cooperative efforts can promote the transition of groundbreaking non-invasive technologies from experimental contexts to extensive clinical application [1], [59].

6. CONCLUSION

Non-invasive hemoglobin estimation has made significant strides in enhancing patient care. AI and smartphone-based technologies, such as spectrophotometric systems and deep learning, offer safer, more accessible alternatives to traditional blood tests. These innovations improve monitoring for conditions like anemia and COPD while minimizing discomfort and risks. Integrating AI and IoT expands healthcare applications, though challenges like racial bias in pulse oximetry and population variability remain. Advancing algorithms, mobile apps, and standard protocols can enhance accuracy and fairness. Collaboration among healthcare and tech experts is vital to ensure the broad adoption of non-invasive diagnostics in diverse settings. Non-invasive hemoglobin estimation has advanced, but challenges remain, including precision across populations and the need for standardized protocols. Current methods like pulse oximetry face high costs and operational complexity. IoT integration enables broader health monitoring, while wearable tech and mobile apps improve accuracy and accessibility, addressing global health inequalities. Future efforts should enhance algorithms, standardize imaging protocols, and ensure consistency across diverse groups. Collaboration among experts is crucial to refine these technologies and promote their widespread adoption in decentralized healthcare settings.

ACKNOWLEDGEMENTS

The work was funded by the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia through the Regular of Fundamental Research Grant, under contract number 131/PFR/LPPMUAD/VI/2024. This research is a collaboration between the Faculty of Industrial Technology and the Faculty of Public Health, Universitas Ahmad Dahlan. The Embedded System and Power Electronics Research Group (ESPERG) also supports this project.

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